



US009142407B2

(12) **United States Patent**  
**Chen et al.**

(10) **Patent No.:** **US 9,142,407 B2**  
(45) **Date of Patent:** **Sep. 22, 2015**

(54) **SEMICONDUCTOR STRUCTURE HAVING  
SETS OF III-V COMPOUND LAYERS AND  
METHOD OF FORMING THE SAME**

(71) Applicants: **Chi-Ming Chen**, Zhubei (TW);  
**Po-Chun Liu**, Hsinchu (TW); **Chung-Yi  
Yu**, Hsinchu (TW); **Chia-Shiung Tsai**,  
Hsinchu (TW)

(72) Inventors: **Chi-Ming Chen**, Zhubei (TW);  
**Po-Chun Liu**, Hsinchu (TW); **Chung-Yi  
Yu**, Hsinchu (TW); **Chia-Shiung Tsai**,  
Hsinchu (TW)

(73) Assignee: **TAIWAN SEMICONDUCTOR  
MANUFACTURING COMPANY,  
LTD.** (TW)

(\*) Notice: Subject to any disclaimer, the term of this  
patent is extended or adjusted under 35  
U.S.C. 154(b) by 0 days.

(21) Appl. No.: **13/743,045**

(22) Filed: **Jan. 16, 2013**

(65) **Prior Publication Data**

US 2014/0197418 A1 Jul. 17, 2014

(51) **Int. Cl.**

**H01L 29/66** (2006.01)

**H01L 21/02** (2006.01)

**H01L 29/778** (2006.01)

**H01L 29/15** (2006.01)

**H01L 29/20** (2006.01)

(52) **U.S. Cl.**

CPC ..... **H01L 21/0254** (2013.01); **H01L 21/0251**  
(2013.01); **H01L 21/02458** (2013.01); **H01L**  
**21/02505** (2013.01); **H01L 29/157** (2013.01);

**H01L 29/66462** (2013.01); **H01L 29/7787**  
(2013.01); **H01L 29/2003** (2013.01)

(58) **Field of Classification Search**

CPC ..... H01L 29/7787; H01L 29/157; H01L  
29/2003; H01L 29/6642

USPC ..... 257/192, 194

See application file for complete search history.

(56) **References Cited**

**U.S. PATENT DOCUMENTS**

8,410,525 B2 *	4/2013	Sato	257/194
2004/0195562 A1 *	10/2004	Munns	257/1
2005/0263791 A1 *	12/2005	Yanagihara et al.	257/194
2006/0261356 A1 *	11/2006	Iwakami et al.	257/80
2012/0326160 A1 *	12/2012	Yanagihara et al.	257/76

\* cited by examiner

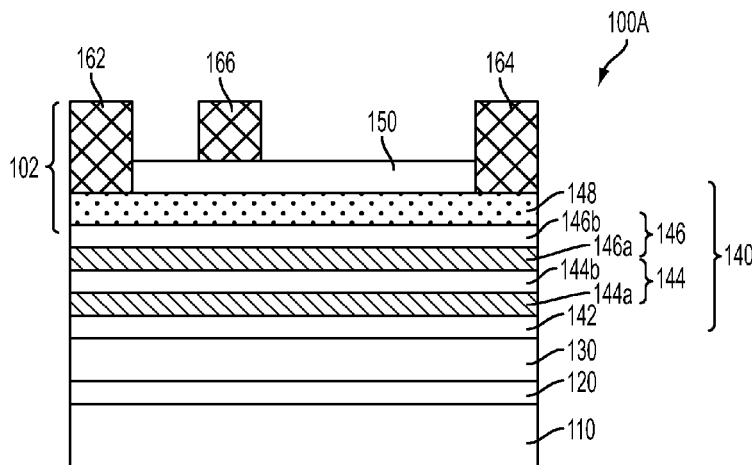
*Primary Examiner* — Tan N Tran

(74) *Attorney, Agent, or Firm* — Lowe Hauptman & Ham,  
LLP

(57) **ABSTRACT**

A semiconductor structure includes a substrate, a first III-V compound layer over the substrate, one or more sets of III-V compound layers over the first III-V compound layer, a second III-V compound layer over the one or more sets of III-V compound layers, and an active layer over the second III-V compound layer. The first III-V compound layer has a first type doping. Each of the one or more sets of III-V compound layers includes a lower III-V compound layer and an upper III-V compound layer over the lower III-V compound layer. The upper III-V compound layer having the first type doping, and the lower III-V compound layer is at least one of undoped, unintentionally doped having a second type doping, or doped having the second type doping. The second III-V compound layer is either undoped or unintentionally doped having the second type doping.

**20 Claims, 5 Drawing Sheets**



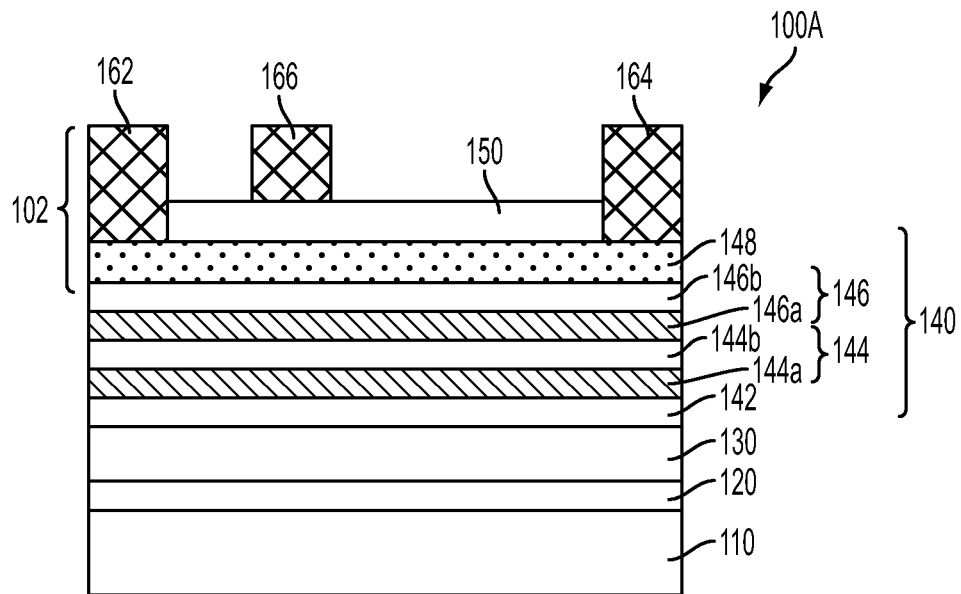


FIG. 1A

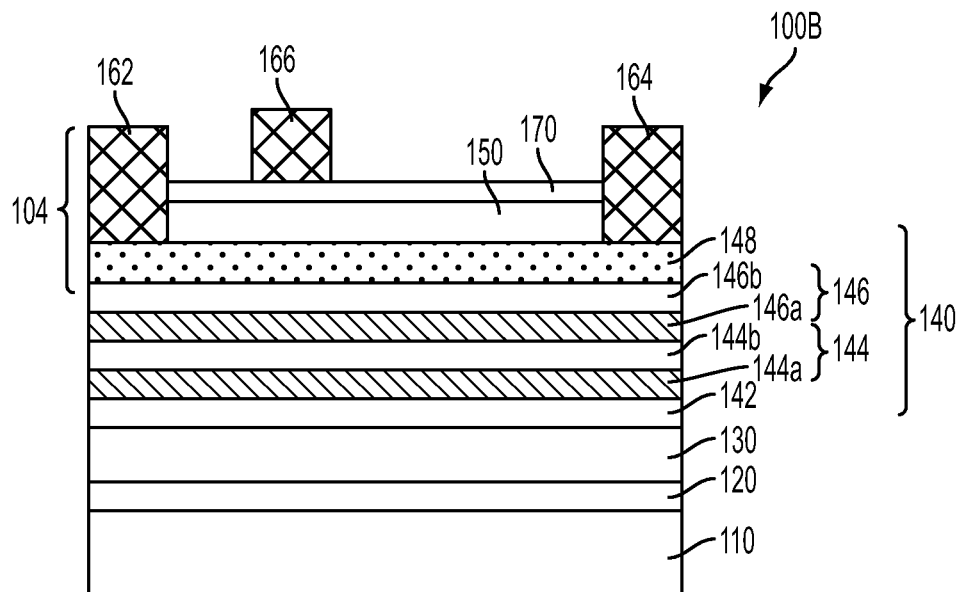


FIG. 1B

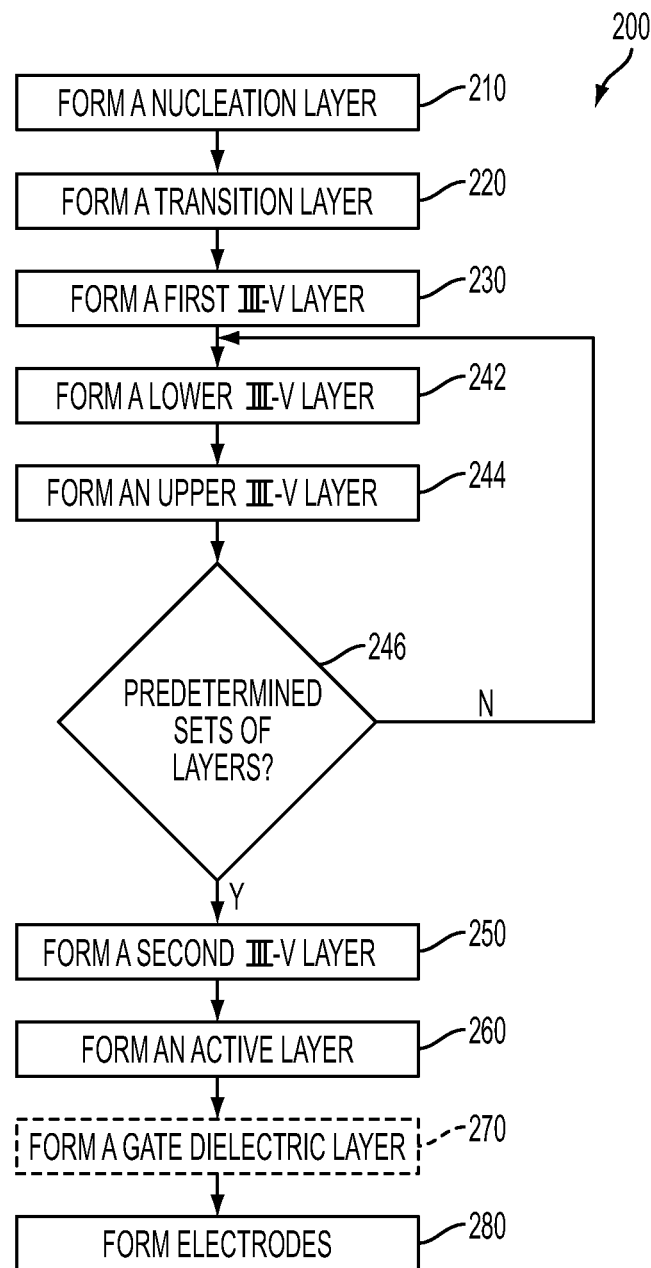


FIG. 2

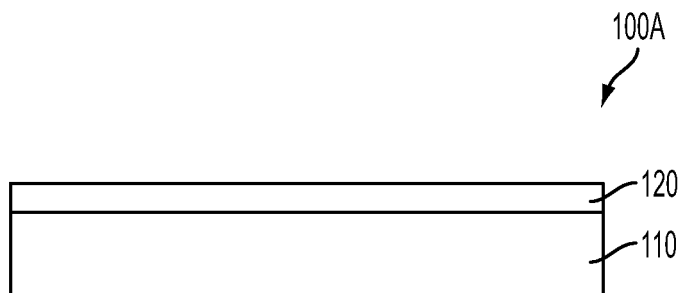


FIG. 3A

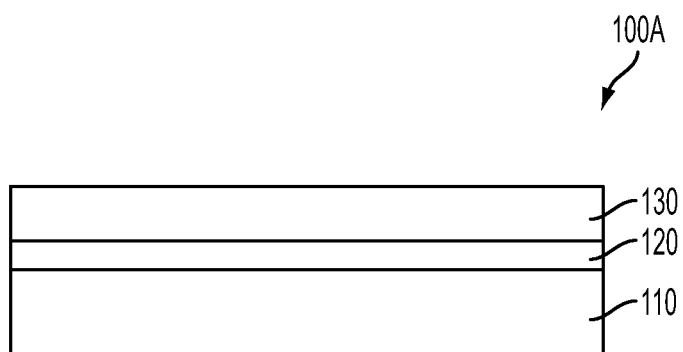


FIG. 3B

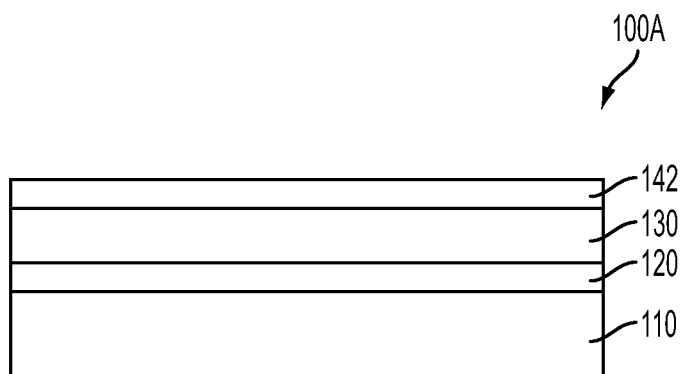


FIG. 3C

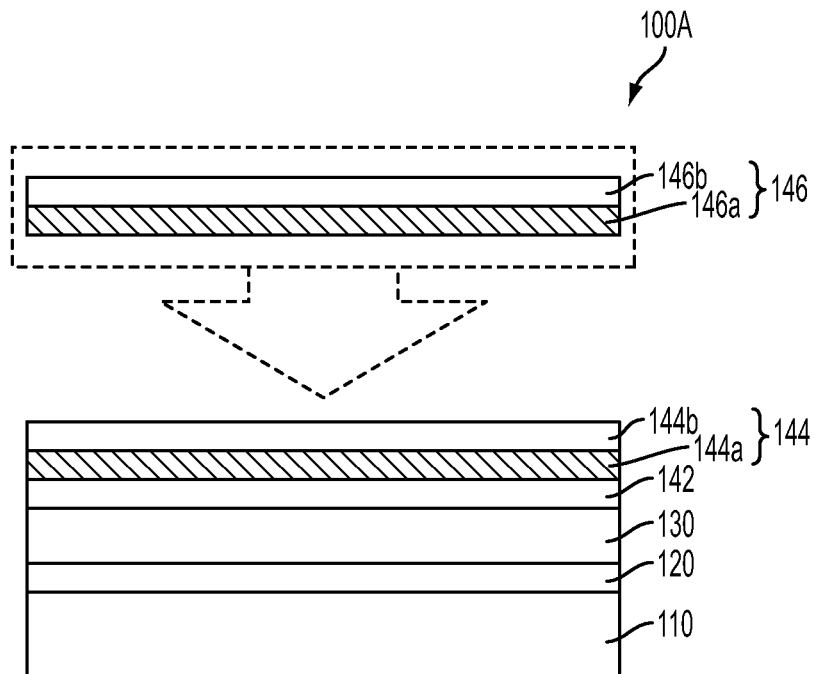


FIG. 3D

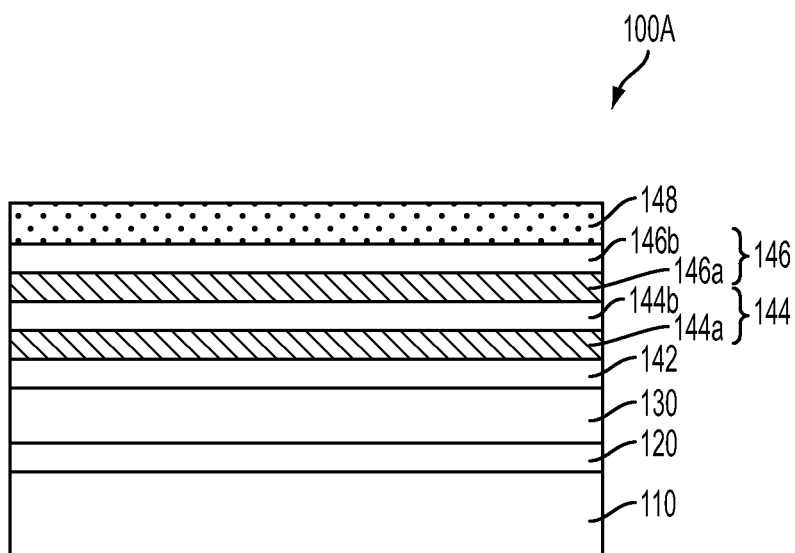


FIG. 3E

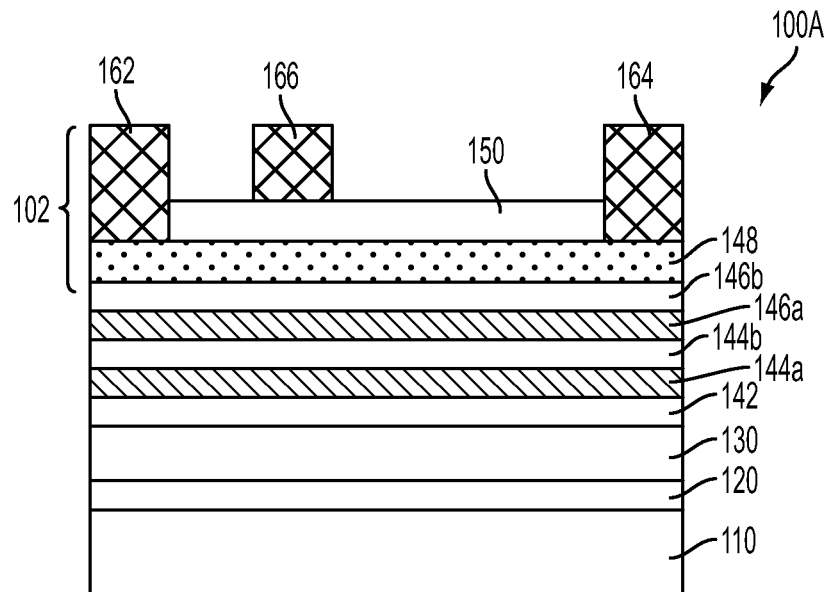


FIG. 3F

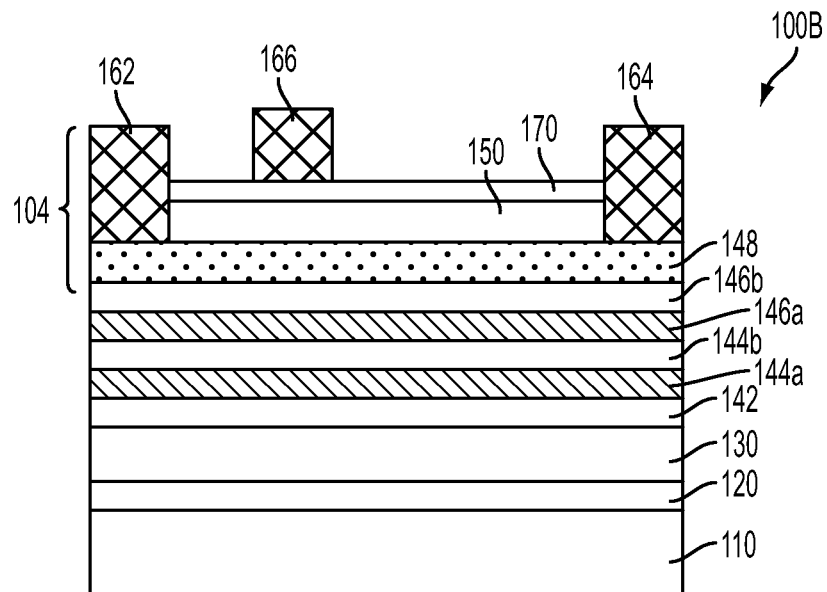


FIG. 3G

# SEMICONDUCTOR STRUCTURE HAVING SETS OF III-V COMPOUND LAYERS AND METHOD OF FORMING THE SAME

## BACKGROUND

In many semiconductor integrated circuits, Group III-Group V compounds (in the periodic table of elements), or III-V compounds, are used to form various electrical devices, such as high power field-effect transistors, high frequency transistors, high electron mobility transistors (HEMTs), or metal-insulator-semiconductor field-effect transistors (MIS-FETs). One example of III-V compounds used in semiconductor integrated circuits is gallium nitride (GaN). In many applications, the electrical devices are formed on a buffer layer, which is intended to be an undoped III-V compound layer. However, because of the presence of oxygen, silicon, and/or other impurity elements in the processing chamber for forming the buffer layer, the buffer layer usually becomes an unintentionally doped III-V compound layer having N-type doping. Thus, compared with the undoped version, the unintentionally doped buffer layer potentially provides a relatively low resistance path for leakage currents.

## DESCRIPTION OF THE DRAWINGS

One or more embodiments are illustrated by way of example, and not by limitation, in the figures of the accompanying drawings, wherein elements having the same reference numeral designations represent like elements throughout and wherein:

FIG. 1A is a cross-sectional view of a semiconductor structure including a high electron mobility transistor (HEMT) in accordance with some embodiments;

FIG. 1B is a cross-sectional view of a semiconductor structure including a metal-insulator-semiconductor field-effect transistor (MISFET) in accordance with some embodiments;

FIG. 2 is a flow chart of a method of forming a HEMT or a MISFET in accordance with one or more embodiments;

FIGS. 3A-3F are cross-sectional views of a semiconductor structure including a HEMT in various manufacturing stages in accordance with one or more embodiments; and

FIG. 3G, in conjunction with FIGS. 3A-3E, is a cross-sectional view of a semiconductor structure including a HEMT in accordance with one or more embodiments.

## DETAILED DESCRIPTION

It is understood that the following disclosure provides one or more different embodiments, or examples, for implementing different features of the disclosure. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, examples and are not intended to be limiting. In accordance with the standard practice in the industry, various features in the drawings are not drawn to scale and are used for illustration purposes only.

Moreover, spatially relative terms, for example, “lower,” “upper,” “horizontal,” “vertical,” “above,” “below,” “up,” “down,” “top,” “bottom,” “left,” “right,” etc. as well as derivatives thereof (e.g., “horizontally,” “downwardly,” “upwardly,” etc.) are used for ease of the present disclosure of one features relationship to another feature. The spatially relative terms are intended to cover different orientations of the device including the features.

FIG. 1A is a cross-sectional view of a semiconductor structure 100A including an HEMT 102 in accordance with some

embodiments. The semiconductor structure 100A includes a substrate 110. In some embodiments, the substrate 110 includes a silicon carbide (SiC) substrate, sapphire substrate, or a silicon substrate. The semiconductor structure 100A further includes a nucleation layer 120 over the substrate, a transition layer 130 over the nucleation layer, a buffer layer 140 over the transition layer, an active layer 150 over the buffer layer, a source electrode 162 and a drain electrode 164 over the buffer layer, and a gate electrode over the active layer. The buffer layer 140 includes III-V compound layers 142, 144a, 144b, 146a, 146b, and 148 stacked one over another. III-V compound layers 144a and 144b are collectively referred to as a set of III-V compound layers 144, and III-V compound layers 146a and 146b are collectively referred to as another set of III-V compound layers 146.

Nucleation layer 120 has a lattice structure and thermal expansion coefficient (TEC) suitable for bridging the lattice mismatch and TEC mismatch between the substrate 110 and the buffer layer 140. In some embodiments, nucleation layer 120 has aluminum nitride (AlN). In some embodiments, nucleation layer 120 has a thickness ranging from 150 to 300 nanometers (nm). Transition layer 130 further facilitates gradual changes of lattice structures and TECs between the nucleation layer 120 and the buffer layer 140. In some embodiments, when the III-V compound layers 142, 144a, 144b, 146a, 146b, and 148 include gallium nitride (GaN), the transition layer 130 is a graded aluminum-gallium nitride ( $\text{Al}_x\text{Ga}_{(1-x)}\text{N}$ , x is the aluminum content ratio in the aluminum-gallium constituent) layer. In some embodiments, the graded aluminum gallium nitride layer includes multiple layers each having a decreased ratio x (from a layer adjoining the nucleation layer 120 to that adjoin the buffer layer 140, or from the bottom to the top portions of the graded aluminum gallium nitride layer). In at least one embodiment, the graded aluminum gallium nitride layer has four layers whose ratios x are 0.75, 0.5, 0.25, and 0.1, from the bottom to the top. In some embodiments, instead of having multiple layers, the graded aluminum gallium nitride layer has a continuous gradient of the ratio x. In some embodiments, transition layer 130 has a thickness ranging from 500 to 1000 nm.

In some embodiments, nucleation layer 120 and/or transition layer 130 are omitted, and thus the III-V compound layer 142 is directly on the substrate 110.

In the embodiment depicted in FIG. 1A, III-V compound layers 142, 144b, and 146b have P-type doping, and III-V compound layers 144a and 146a have N-type doping. Moreover, buffer layer 140 provides an undoped or unintentionally doped III-V compound layer (e.g., the second III-V layer 148) on which the HEMT 102 is formed. Because, in some application, the second III-V layer 148 is unintentionally doped and has N-type doping, the buffer layer 140 includes three P—N junctions between layers 142 and 144a, 144b and 146a, and 146b and 148. When the substrate 110 is biased to a supply voltage lower than the voltages at the electrodes 162, 164, and 166 of the HEMT 102, the P—N junctions 142/144a, 144b/146a, and 146b/148 are reversed-biased. Therefore, compared with the a configuration where a buffer layer includes only a single undoped or unintentionally doped III-V compound layer, buffer layer 140 provides a relatively high resistance path for leakage currents by having reversed-biased PN junctions.

In some embodiments, the III-V compound layer 144a is at least one of undoped, unintentionally doped having N-type doping, or doped having the N-type doping. In some embodiments, the III-V compound layer 146a is at least one of undoped, unintentionally doped having N-type doping, or doped having the N-type doping. In some embodiments, the

second III-V compound layer **148** is either undoped or unintentionally doped having the N-type doping.

In some embodiments, layer **144a** (N-type doping) is configured to cause a depletion region formed within layer **142** (P-type doping), and a thickness of layer **142** is set to be sufficient to prevent the depletion region from extending through the entire thickness of the layer **142**. In some embodiments, III-V compound layer **142** comprises GaN and has a thickness greater than 0.15 micrometers ( $\mu\text{m}$ ). In some embodiments, III-V compound layer **142** comprises GaN and has a doping concentration greater than  $1.0 \times 10^{19}$  atoms/ $\text{cm}^3$ .

In the embodiment depicted in FIG. 1A, two sets (**144** and **146**) of III-V compound layers are depicted. Each of the two sets of layers includes a lower layer **144a** or **146a** having N-type doping and an upper layer **144b** and **146b** having P-type doping. In some embodiments, there are more or less than two sets of III-V compound layers. In some embodiments, the number of sets of III-V compound layers ranges from 1 to 200.

In some embodiments, III-V compound layer **146a** is configured to cause a depletion region formed within III-V compound layer **144b**, and a thickness of layer **144b** is set to be sufficient to prevent the depletion region from extending through the entire thickness of layer **144b**. In some embodiments, III-V compound layer **148** is configured to cause a depletion region formed within III-V compound layer **146b**, and a thickness of layer **146b** is set to be sufficient to prevent the depletion region from extending through the entire thickness of layer **146b**. In some embodiments, in one of the one or more sets of III-V compound layers, the upper III-V compound layer **144b** or **146b** has a thickness no less than that of the corresponding layer **146a** or **148** immediately thereon. In some embodiments, each of the layers **144a**, **144b**, **146a**, or **146b** has a thickness ranging from 0.05  $\mu\text{m}$  to 0.1  $\mu\text{m}$ .

In some embodiments, III-V compound layers **144a** and **146a** comprise GaN and have a doping concentration no greater than  $1.0 \times 10^{17}$  atoms/ $\text{cm}^3$ . In some embodiments, III-V compound layers **144b** and **146b** comprise GaN and have a doping concentration ranging from  $1.0 \times 10^{15}$  to  $1.0 \times 10^{19}$  atoms/ $\text{cm}^3$ . In some embodiments, all sets of III-V compound layers **144** and **146** have a same configuration. In some embodiments, not all sets of III-V compound layers **144** and **146** have the same configuration.

According to one or more embodiments of this disclosure, the HEMT **102** includes the heterojunction formed between two different semiconductor material layers, such as the active layer **150** and III-V layer **148**. The band gap discontinuity exists between the active layer **150** and the III-V compound layer **148**. The electrons from a piezoelectric effect in the active layer **150** drop into the III-V compound layer **148**, and thus create a thin layer of highly mobile conducting electrons in the III-V compound layer **148**. This thin layer is also referred to as a two-dimensional electron gas (2-DEG) layer. The 2-DEG layer is formed within the III-V compound layer **148** near an interface of the active layer **150** and the III-V compound layer **148**, and between the electrodes **162** and **164**. The 2-DEG layer is used as a channel of the HEMT **102**. In some embodiments, the channel has high electron mobility because the III-V compound layer **148** is undoped or unintentionally doped, and the electrons can move freely without collision or with substantially reduced collisions with impurities. The active layer **150** is also known as a donor-supply layer, and the III-V layer **148** is also known as a channel layer.

In some embodiments, the channel layer and the donor-supply layer are compounds made from the III-V groups in the periodic table of elements. In some embodiments, the

channel layer and the donor-supply layer are different from each other in composition. In some embodiments, the III-V compound layer **148** is undoped or unintentionally doped. In some embodiments, the active layer **150** is intentionally doped. In some embodiments when III-V layer **148** comprises GaN, active layer **150** comprises AlN, AlGaIn, or a combination thereof.

Electrode **162** and electrode **164** are disposed on the III-V compound layer **148**, and electrode **166** is disposed on the active layer **150**. Electrode **162** is used as a source electrode, the electrode **164** is used as a drain electrode, and the electrode **166** is used as a gate electrode of the HEMT **102**. When a voltage is applied to the gate electrode **166**, a device current of the HEMT **102** could be modulated.

FIG. 1B is a cross-sectional view of a semiconductor structure **100B** including an MISFET **104** in accordance with some embodiments. Compared with the semiconductor structure **100B**, a dielectric layer **170** is disposed over the active layer **150** and below the gate electrode **166**. In some embodiments, the dielectric layer **170** comprises silicon oxide ( $\text{SiO}_2$ ), silicon nitride ( $\text{Si}_3\text{N}_4$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), tantalum oxide ( $\text{Ta}_2\text{O}_5$ ), titanium oxide ( $\text{TiO}_2$ ), zinc oxide ( $\text{ZnO}_2$ ), hafnium oxide ( $\text{HfO}_2$ ), or a combination thereof.

FIG. 2 is a flow chart of a method **200** of forming a semiconductor structure **100A** including a HEMT **102** or a semiconductor structure **100B** including a MISFET **104** in accordance with one or more embodiments. FIGS. 3A-3F are cross-sectional views of a semiconductor structure **100A** including HEMT **102** in various manufacturing stages in accordance with one or more embodiments. It is understood that additional operations may be performed before, during, and/or after the method **200** depicted in FIG. 2, and that some other processes may only be briefly described herein.

As depicted in FIG. 2 and FIG. 3A, the semiconductor structure **100A** includes a substrate **110**. In some embodiments, substrate **110** is a (111) silicon substrate.

In operation **210**, a nucleation layer **120** is formed over substrate **110**. In some embodiments, nucleation layer **120** comprises AlN. In some embodiments, the formation of nucleation layer **120** is performed by a metal-organic chemical vapor deposition (MOCVD) process, using aluminum-containing precursor and nitrogen-containing precursor. In some embodiments, the aluminum-containing precursor includes trimethylaluminum (TMA), triethylaluminum (TEA), or other suitable chemical. In some embodiments, the nitrogen-containing precursor includes ammonia, tertiarybutylamine (TBAm), phenyl hydrazine, or other suitable chemical. In some embodiments, the nucleation layer **120** comprises a material other than AlN. In some embodiments, nucleation layer **120** has a thickness ranging from 150 to 300 nm.

In some embodiments, nucleation layer **120** is omitted, and thus operation **210** is omitted.

The process proceeds to operation **220**. As depicted in FIG. 2 and FIG. 3B, in operation **220**, a transition layer **130** is formed over nucleation layer **120**. In some embodiments, transition layer **130** is a graded aluminum-gallium nitride ( $\text{Al}_x\text{Ga}_{(1-x)}\text{N}$ ) layer. In some embodiments, the graded aluminum gallium nitride layer has two or more of aluminum-gallium nitride layers each having a different ratio  $x$  decreased from the bottom to the top. In some embodiments, each of the two or more of aluminum-gallium nitride layers is formed by performing a MOCVD process, using aluminum-containing precursor, gallium-containing precursor, and nitrogen-containing precursor. In some embodiments, the aluminum-containing precursor includes TMA, TEA, or other suitable chemical. In some embodiments, the gallium-

containing precursor includes trimethylgallium (TMG), triethylgallium (TEG), or other suitable chemical. In some embodiments, the nitrogen-containing precursor includes ammonia, TBAm, phenyl hydrazine, or other suitable chemical. In some embodiments, the graded aluminum gallium nitride layer has a continuous gradient of the ratio  $x$  gradually decreased from the bottom to the top. In some embodiments, the graded aluminum-gallium nitride layer is formed by performing a MOCVD process. In some embodiments, the transition layer **130** has a thickness ranging from 500 to 1000 nm.

In some embodiments, transition layer **130** is omitted, and thus operation **220** is omitted.

The process proceeds to operation **230**. As depicted in FIG. 2 and FIG. 3C, in operation **230**, a first III-V compound layer **142** having a first-type doping is formed over substrate **110**, nucleation layer **120**, and/or transition layer **130**. In some embodiments, the first type doping is P-type doping. In some embodiments, first III-V compound layer **142** comprises GaN, and the P-type doping is implemented by using dopants including carbon, iron, magnesium, or zinc. In at least one embodiment, when the manufacture of HEMT **102** is completed, a layer (such as layer **142a**) over first III-V compound layer **142** is configured to cause a depletion region formed within the first III-V compound layer **142**. As such, a thickness of first III-V compound layer **142** is set to be sufficient to prevent the depletion region from extending through the entire thickness of the first III-V compound layer **142**.

In some embodiments, first III-V compound layer **142** has a thickness greater than 0.15  $\mu\text{m}$ . In some embodiments, the first III-V compound layer has a doping concentration greater than  $1.0 \times 10^{19}$  atoms/cm<sup>3</sup>. In some embodiments, first III-V compound layer **142** is formed by performing a MOCVD process, using gallium-containing precursor and nitrogen-containing precursor.

The process proceeds to operation **242**. As depicted in FIG. 2 and FIG. 3D, in operation **242**, a lower III-V layer **144a** corresponding to the III-V compound layer **142** in FIG. 1A is formed over the first III-V compound layer **142**. In some embodiments, the lower III-V layer **144a** is undoped, unintentionally doped having a second type doping, or doped having the second type doping. In some embodiments, the second type doping is N-type doping. In some embodiments, lower III-V compound layer **144a** comprises GaN, and the N-type doping is implemented by using dopants including silicon or oxygen. In some embodiments, lower III-V compound layer **144a** has a doping concentration no greater than  $1.0 \times 10^{17}$  atoms/cm<sup>3</sup>. In some embodiments, lower III-V compound layer **144a** has a thickness ranging from 0.05  $\mu\text{m}$  to 0.1  $\mu\text{m}$ . In some embodiments, lower III-V compound layer **144a** is formed by performing a MOCVD process, using gallium-containing precursor and nitrogen-containing precursor.

The process proceeds to operation **244**, where an upper III-V compound layer **144b** is formed over the lower III-V compound layer **144a**. The lower III-V compound layer **144a** and the upper III-V compound layer **144b** are collectively referred to as a first set of III-V compound layers **144**. In some embodiments, the upper III-V layer **144b** has the first type doping (e.g., the P-type doping). In some embodiments, upper III-V compound layer **144b** comprises GaN. In at least one embodiment, when the manufacture of HEMT **102** is completed, a layer (such as layer **146a** or layer **148** if layers **146a** and **146b** are omitted) over upper III-V compound layer **144b** is configured to cause a depletion region formed within the upper III-V compound layer **144b**. As such, a thickness of upper III-V compound layer **144b** is set to be sufficient to prevent the depletion region from extending through the

entire thickness of the upper III-V compound layer **144b**. In some embodiments, thickness of upper III-V compound layer **144b** is set to be greater than a thickness of a layer immediately on the upper III-V compound layer **144b**.

In some embodiments, upper III-V compound layer **144b** has a doping concentration  $1.0 \times 10^{15}$  to  $1.0 \times 10^{19}$  atoms/cm<sup>3</sup>. In some embodiments, upper III-V compound layer **144b** has a thickness ranging from 0.05  $\mu\text{m}$  to 0.1  $\mu\text{m}$ . In some embodiments, upper III-V compound layer **144b** is formed by performing a MOCVD process, using gallium-containing precursor and nitrogen-containing precursor.

The process proceeds to operation **246**, where whether a predetermined number of sets of III-V compound layers similar to the set of III-V compound layers **144** has been formed in the semiconductor structure **100A**. In some embodiments, the predetermined number is set to be a number ranging from 1 to 200. If it is determined that at least another set of III-V compound layers, such as the set of III-V compound layers **146**, needs to be further formed, the process proceeds to operation **242** to form lower III-V compound layer **146a** and operation **244** to form upper compound **146b** for the set of III-V compound layers **146**. In some embodiments, the set of III-V compound layers **144** and the set of III-V compound layers **146** have a similar configuration and are fabricated by a similar process. In some embodiments, not all the predetermined sets of III-V compound layers have the same thickness and/or doping concentration. In at least one embodiment, all the predetermined sets of III-V compound layers have undoped or N-type lower III-V layers and P-type upper III-V layers.

In operation **246**, if no further set of III-V compound layers is needed, the process proceeds to operation **250**.

As depicted in FIG. 2 and FIG. 3E, in operation **250**, a second III-V compound layer **148** is formed over the one or more sets of III-V compound layers **144** and **146**. Second III-V compound layer **148** is undoped, or unintentionally doped having the second type doping (e.g. N-type doping). In some embodiments, Second III-V compound layer **148** comprises GaN. In some embodiments, second III-V compound layer **148** has a thickness ranging from 0.25 to 0.5  $\mu\text{m}$ . In some embodiments, the first III-V compound layer has a doping concentration no greater than  $1.0 \times 10^{16}$  atoms/cm<sup>3</sup>. In some embodiments, second III-V compound layer **148** is formed by performing a MOCVD process, using gallium-containing precursor and nitrogen-containing precursor.

The process proceeds to operation **260**. As depicted in FIG. 2 and FIG. 3F, in operation **260**, an active layer **150** corresponding to the active layer **150** in FIG. 1 is formed over the second III-V compound layer **148**. In some embodiments, active layer **150** includes AlGaIn, aluminum-gallium Arsenide (AlGaAs), aluminum-Indium phosphide (AlInP), or a combination thereof. In some embodiments, active layer **150** includes AlGaIn, where an aluminum content ratio in the aluminum-gallium constituent ranges from 0.1 to 0.25. In some embodiments, active layer **150** has a thickness ranging from 15 to 30 nm. In some embodiments, active layer **150** is formed by performing a MOCVD process, using aluminum-containing precursor, gallium-containing precursor, and nitrogen-containing precursor.

For forming HEMT **102**, operation **270** is omitted and the process proceeds to operation **280**. As depicted in FIG. 2 and FIG. 3F, in operation **280**, electrodes **162** and **164** are formed over second III-V compound layer **148**, and electrode **166** is formed over active layer **150**. In some embodiments, a patterned mask layer (i.e., a photoresistive layer) is formed on the upper surface of active layer **150**, and an etching process is performed to remove a portion of the active layer **150** to

form openings partially exposing an upper surface of second III-V compound layer **148**. A metal layer is then deposited over patterned active layer **150** and fills the openings and contacts the second III-V compound layer **148**. Another patterned photoresist layer is formed over the metal layer, and the metal layer is etched to form electrodes **162** and **164** over the openings and electrode **166** over the upper surface of active layer **150**. In some embodiments, the metal layer for forming electrodes **162**, **164**, and **166** includes one or more conductive materials. In some embodiments, electrodes **162**, **164**, and **166** include one or more layers of conductive materials. In at least one embodiment, electrodes **162**, **164**, and **166** include at least one barrier layer contacting the second III-V compound layer **148** and/or the active layer **150**.

FIG. 3G is a cross-sectional view of a semiconductor structure **100B** including a MISFET **104** in accordance with some embodiments. FIG. 3G, in conjunction with FIGS. 3A-3E are cross-sectional views of the semiconductor structure **100B** in various manufacturing stages in accordance with one or more embodiments.

In a process for forming the semiconductor structure **100B**, after performing the operations similar to operations **210** to **260**, the process proceeds to operation **260**. As depicted in FIGS. 2 and 3G, in operation **260**, a dielectric layer **170** is formed over the active layer **150**. In some embodiments, dielectric layer **170** includes silicon oxide ( $\text{SiO}_2$ ), silicon nitride ( $\text{Si}_3\text{N}_4$ ), aluminum oxide ( $\text{Al}_2\text{O}_3$ ), tantalum oxide ( $\text{Ta}_2\text{O}_5$ ), titanium oxide ( $\text{TiO}_2$ ), zinc oxide ( $\text{ZnO}_2$ ), hafnium oxide ( $\text{HfO}_2$ ), or a combination thereof. In at least one embodiment, dielectric layer **170** has a thickness ranging from 3 nm to 100 nm. In some embodiments, dielectric layer **170** is formed by any proper fabrication technique, such as MOCVD, chemical vapor deposition (CVD), physical vapor deposition (PVD), atomic layer deposition (ALD), or thermal oxidation. In some embodiments, the dielectric layer **170** provides further isolation to prevent gate leakage.

The process then proceeds to operation **280**, where openings through the active layer **150** and the dielectric layer **170** are formed, electrodes **162** and **164** are formed on the second III-V compound layer **148**, and electrode **166** is formed on the dielectric layer **170**. The operation **280** for forming the semiconductor structure **100B** is similar to operation **280** for forming the semiconductor structure **100A**, and thus description thereof is omitted.

In accordance with one embodiment, a semiconductor structure includes a substrate, a first III-V compound layer over the substrate, one or more sets of III-V compound layers over the first III-V compound layer, a second III-V compound layer over the one or more sets of III-V compound layers, and an active layer over the second III-V compound layer. The first III-V compound layer has a first type doping. Each of the one or more sets of III-V compound layers includes a lower III-V compound layer and an upper III-V compound layer over the lower III-V compound layer. The upper III-V compound layer having the first type doping, and the lower III-V compound layer is at least one of undoped, unintentionally doped having a second type doping, or doped having the second type doping. The second III-V compound layer is either undoped or unintentionally doped having the second type doping.

In accordance with another embodiment, a semiconductor structure includes a substrate, a graded aluminum gallium nitride (AlGaIn) layer over the substrate, a first gallium nitride (GaN) layer over the AlGaIn substrate, one or more sets of GaN layers over the first GaN layer, and a second GaN layer over the one or more sets of GaN layers. The first GaN layer has P-type doping. Each of the one or more sets of GaN layers

includes a lower GaN layer and an upper GaN layer on the lower GaN layer. The upper GaN layer has the P-type doping, and the lower GaN layer is at least one of undoped, unintentionally doped having N-type doping, or doped having the N-type doping. The second GaN layer is either undoped or unintentionally doped having the N-type doping. The semiconductor structure includes an active layer over the second GaN layer, a source electrode over the second GaN layer, a drain electrode over the second GaN layer, and a gate electrode between the source electrode and the drain electrode and over the active layer.

In accordance with another embodiment, a method of forming a semiconductor structure includes forming a first III-V compound layer having a first-type doping over a substrate. One or more sets of III-V compound layers are formed over the first III-V compound layer. Each of the one or more sets of III-V compound layers includes a lower III-V compound layer and an upper III-V compound layer over the lower III-V compound layer. The upper III-V compound layer has the first type doping, and the lower III-V compound layer is at least one of undoped, unintentionally doped having a second type doping, or doped having the second type doping. A second III-V compound layer is formed over the one or more sets of III-V compound layers. The second III-V compound layer is either undoped or unintentionally doped having the second type doping. An active layer is formed over the second III-V compound layer.

The foregoing outlines features of several embodiments so that those skilled in the art may better understand the aspects of the present disclosure. Those skilled in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. Those skilled in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions, and alterations herein without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A semiconductor structure, comprising:

a substrate;

a first III-V compound layer over the substrate, the first III-V compound layer having a first type doping;

one or more sets of III-V compound layers over the first III-V compound layer, each set of the one or more sets of III-V compound layers comprising a lower III-V compound layer and an upper III-V compound layer over the lower III-V compound layer, the upper III-V compound layer having the first type doping, and the lower III-V compound layer being at least one of undoped, unintentionally doped having a second type doping, or doped having the second type doping;

a second III-V compound layer over the one or more sets of III-V compound layers, the second III-V compound layer being either undoped or unintentionally doped having the second type doping; and

an active layer over the second III-V compound layer, wherein the first III-V compound layer has a thickness greater than that of the corresponding upper III-V compound layer of any one of the one or more sets of III-V compound layers by at least 0.05  $\mu\text{m}$ , and

wherein, the first III-V compound layer has a doping concentration greater than that of the corresponding upper III-V compound layer of any one of the two or more sets of III-V compound layers.

2. The semiconductor structure of claim 1, wherein the first type doping is P-type doping, and the second type doping is N-type doping.

3. The semiconductor structure of claim 2, wherein the first type doping is implemented by dopants including carbon, iron, magnesium, or zinc.

4. The semiconductor structure of claim 2, wherein the second type doping is implemented by dopants including silicon or oxygen.

5. The semiconductor structure of claim 1, wherein, when a layer over the first III-V compound layer is configured to cause a depletion region formed within the first III-V compound layer, the first III-V compound layer has a thickness sufficient to prevent the depletion region from extending through the entire thickness of the first III-V compound layer.

6. The semiconductor structure of claim 1, wherein the thickness of the first III-V compound layer is greater than 0.15  $\mu\text{m}$ , and the doping concentration of the first III-V compound layer has a doping concentration is greater than  $1.0 \times 10^{19}$  atoms/ $\text{cm}^3$ .

7. The semiconductor structure of claim 1, wherein the upper III-V compound layer of one of the one or more sets of III-V compound layers has a thickness sufficient to prevent a depletion region from extending through the entire thickness of the upper III-V compound layer when a layer over the upper III-V compound layer is configured to cause the depletion region formed within the upper III-V compound layer.

8. The semiconductor structure of claim 7, wherein the upper III-V compound layer of the one of the one or more sets of III-V compound layers has a thickness no less than that of the layer immediately on the upper III-V compound layer.

9. The semiconductor structure of claim 1, wherein the upper III-V compound layer of one of the one or more sets of III-V compound layers has a first thickness, a lower III-V compound layer of the one of the one or more sets of III-V compound layers has a second thickness, and the first thickness and the second thickness range from 0.05  $\mu\text{m}$  to 0.1  $\mu\text{m}$ .

10. The semiconductor structure of claim 1, wherein the doping concentration of the upper III-V compound layer of one of the one or more sets of III-V compound layers is between  $1.0 \times 10^{15}$  to  $1.0 \times 10^{19}$  atoms/ $\text{cm}^3$ .

11. The semiconductor structure of claim 1, the lower III-V compound layer of one of the one or more sets of III-V compound layers has a doping concentration no greater than  $1.0 \times 10^{17}$  atoms/ $\text{cm}^3$ .

12. The semiconductor structure of claim 1, wherein the first III-V compound layer, the second III-V compound layer, and the one or more sets of III-V compound layers are gallium nitride (GaN) layers.

13. A semiconductor structure, comprising:

a substrate;

a graded aluminum gallium nitride (AlGaIn) layer over the substrate;

a first gallium nitride (GaN) layer over the graded AlGaIn layer, the first GaN layer having P-type doping;

one or more sets of GaN layers over the first GaN layer, each set of the one or more sets of GaN layers comprising a lower GaN layer and an upper GaN layer on the lower GaN layer, the upper GaN layer having the P-type doping, and the lower GaN layer being at least one of undoped, unintentionally doped having N-type doping, or doped having the N-type doping;

a second GaN layer over the one or more sets of GaN layers, the second GaN layer being either undoped or unintentionally doped having the N-type doping;

an active layer over the second GaN layer;

a source electrode over the second GaN layer;

a drain electrode over the second GaN layer; and

a gate electrode between the source electrode and the drain electrode and over the active layer.

14. The semiconductor structure of claim 13, wherein the active layer comprises AlN or AlGaIn.

15. The semiconductor structure of claim 14, further comprising:

a dielectric layer between the gate electrode and the active layer.

16. The semiconductor structure of claim 13, wherein one of the one or more sets of GaN layers is directly on the first GaN layer, the lower III-V compound layer of the one pair of the one or more sets of GaN layers is configured to cause a depletion region formed within the first GaN layer, and the first GaN layer has a thickness sufficient to prevent the depletion region from extending through the entire thickness of the first GaN layer.

17. The semiconductor structure of claim 13, wherein the upper GaN of one of the one or more sets of GaN layers has a doping concentration ranging from  $1.0 \times 10^{15}$  to  $1.0 \times 10^{19}$  atoms/ $\text{cm}^3$ .

18. The semiconductor structure of claim 13, wherein the lower GaN layer of one of the one or more sets of GaN layers has a doping concentration no greater than  $1.0 \times 10^{17}$  atoms/ $\text{cm}^3$ .

19. A method of forming a semiconductor structure, the method comprising:

forming a first III-V compound layer having a first-type doping over a substrate;

forming one or more sets of III-V compound layers over the first III-V compound layer, each set of the one or more sets of III-V compound layers comprising a lower III-V compound layer and an upper III-V compound layer over the lower III-V compound layer, the upper III-V compound layer having the first type doping, and the lower III-V compound layer being at least one of undoped, unintentionally doped having a second type doping, or doped having the second type doping;

forming a second III-V compound layer over the one or more sets of III-V compound layers, the second III-V compound layer being either undoped or unintentionally doped having the second type doping; and

forming an active layer over the second III-V compound layer,

wherein the first III-V compound layer has a thickness greater than that of the corresponding upper III-V compound layer of any one of the one or more sets of III-V compound layers by at least 0.05  $\mu\text{m}$ , and

wherein, the first III-V compound layer has a doping concentration greater than that of the corresponding upper III-V compound layer of any one of the one or more sets of III—V compound layers.

20. The method of claim 19, wherein the forming the first III-V compound layer, the forming the second III-V compound layer, and the forming the one or more pairs of III-V compound layers are performed by using a metal-organic chemical vapor deposition (MOCVD) process.